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Shifting planting date of *Boro* rice as a climate change adaptation strategy to reduce water use

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ABSTRACT

Suitable adaptation strategies for dry season *Boro* rice cultivation under future climate change scenarios are important for future food security in Bangladesh. This study assessed the effect of shifting trans−/planting date of dry season *Boro* rice as an adaptation strategy, with focus on water requirements under future climate scenarios. Potential crop water requirement, effective rainfall and irrigation requirement to satisfy crop evapotranspiration of *Boro* rice were estimated using CropWat 8.0 for early, normal and late planting dates for 2050s and 2080s. Future climate scenarios were constructed using five global circulation model (GCM) outputs for RCP 4.5 and 8.5 by statistical downscaling and bias correction. Number of days exceeding the threshold temperatures (maximum of 35 °C and minimum of 25 °C) was counted for critical period of *Boro* rice to understand compatibility of the changed planting dates. Results indicate that late planting can substantially reduce irrigation demand by increasing rainfall availability during *Boro* growth duration, but the option is very limited due to both day- and night-time heat stress. An early planting, on the other hand, accounts for high water demand but ensures suitable temperature during the critical growth stages of the crop. The normal planting dates show the possibility of day-time heat stress. So, late planting of temperature-tolerant cultivars or early planting of high-yielding varieties would be recommended based on local water availability. However, adjustment of the planting date is currently limited because high temperature-tolerant cultivars are not available in the study region.

1. Introduction

Climate change affects the water requirement of crops. Irrigation demand will increase in Europe, USA and some parts of Asia, while the irrigated regions in India, Pakistan, and South-Eastern China might experience a slight decrease in irrigation demand (Biemans et al., 2013). Future irrigation demand is projected to exceed local water availability in many places (Wada et al., 2013). According to Hijioka et al. (2014), water scarcity due to increased water demand for population growth and higher standard of living will be a major challenge for most parts of Asia. Development of water saving technologies, increased water productivity, and water reuse could be effective in this regard (Hijioka et al., 2014). However, irrigation for crop agriculture, which is the largest water demand sector in Bangladesh, requires special attention to deal with future water demand management. Improved agricultural practices and irrigation management can play a vital role to cope with the risk of water shortage.

Climate change induced changes in water demand, availability and quality will impact water management decisions. Adaptation measures to ensure proper water balance requires strategies for supply-side as well as demand-side (Bates et al., 2008). One possible solution to reduce water demand for irrigation could be changing the cropping calendar. The changes in climatic parameters during recent decades contributed to reduce irrigation requirements in North-West Bangladesh (Acharjee et al., 2017; Mojid et al., 2015). However, the water demand for crop agriculture has increased due to expansion of irrigated agriculture. Water demand for *Boro* rice will reduce in the future (Acharjee et al., 2017). The total annual water demand for crop cultivation, however, may still increase due to increasing cropping intensity as rice growth duration will become shorter. A shorter growing season of *Boro* rice due to the crop's phenological responses to climate change provides more flexibility to shift planting times.

Climate change will not only result in an increase or decrease in different climatic parameters, but will also cause changes in seasonality and variability of different parameters. There will be large seasonal and regional variations in climatic parameters in South Asia (Wassmann and

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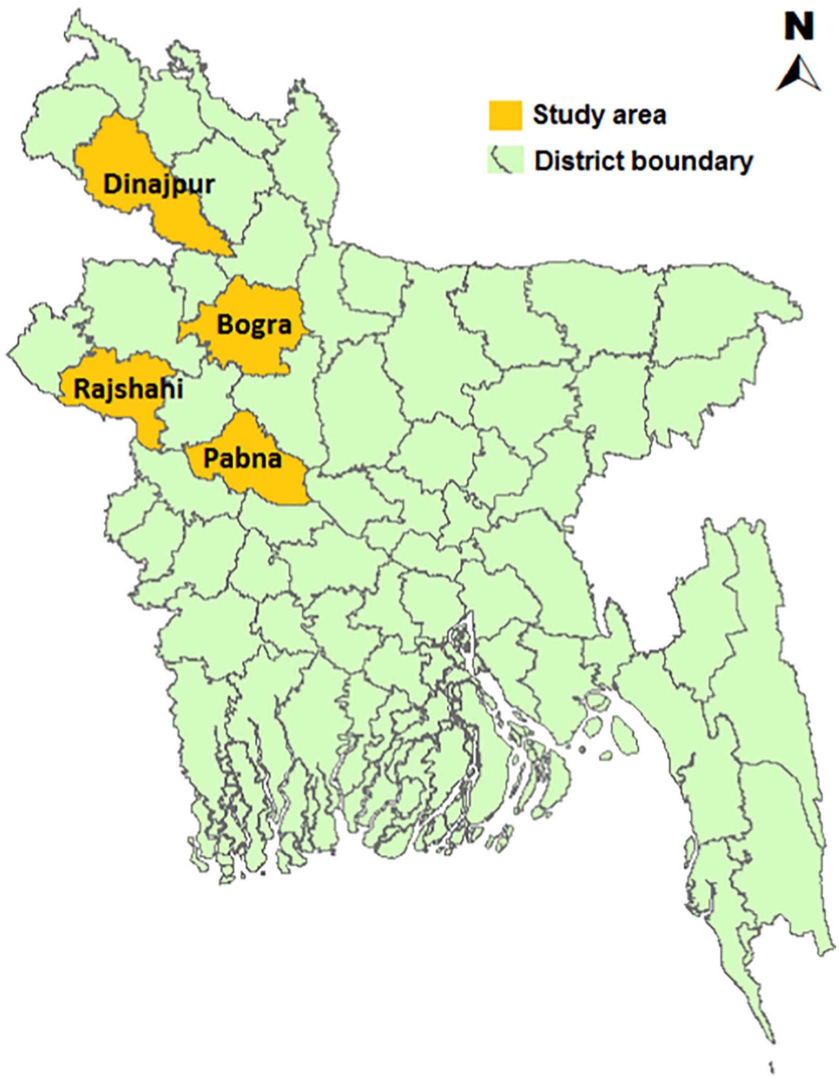

Fig. 1. The location of the study area.

Dobermann, 2007). The contrast in precipitation between wet and dry seasons will increase in the future (IPCC, 2013). Change of planting date of crops could be a simple and effective way to deal with changes in seasonal variability in climatic parameters. Following the climate change, a shift in planting date may allow plants to be exposed to more favourable conditions (Chun et al., 2016). For under developed countries, more emphasis on low-cost strategies is likely to be more effective for large-scale implementation. Farmers can adapt to changed climatic conditions to some degree by changing planting dates, choosing cultivars of different growth duration, or changing crop rotations (Wassmann and Dobermann, 2007). Several researchers have indicated that shifting the rice planting date could be an effective solution to improve rice yields in a changing climate. Simple adaptation options, such as shifting planting dates, can be applied to significantly increase net water productivity (Mainuddin et al., 2011). High-temperature and drought stresses can also be avoided by changing the transplanting date or growth period (Shelley et al., 2016).

Agricultural production in South Asia may reduce by 30% by 2050s if no action is taken to reduce the effects of increasing temperature and hydrologic disruption (Parry et al., 2007). As rice cultivation requires a large quantity of water, both the yield and water requirements are important aspects for optimizing the planting date. Previous studies which assessed the impacts of changing planting date of *Boro* rice in Bangladesh focusing only on yield (Basak et al., 2010; Karim et al., 2012) and disregarded the impact on water use and/or requirements. However, it is also important to understand the impacts of changing planting date on the water requirements of the crop.

Extreme temperature events affect growth and productivity of crops because high temperatures are destructive for plant growth and development. Critical temperatures vary with genotype, duration of critical temperature period, diurnal changes and physiological status of the plant (Yoshida, 1981). Due to climate changes, the number of days with extremely high temperatures will increase potentially reducing crop yield. Changing planting dates can both increase and reduce the risk of yield loss due to extreme temperatures. This study focused on identification of suitable planting date of *Boro* rice that can minimize irrigation requirement without damaging the crop during the critical period by extreme temperatures.

The objectives of the study were to assess the capacity and suitability of shifting planting date of rice as a climate change adaptation option. Several other studies have focused on yield estimation under different planting dates of *Boro* rice. Therefore, we mainly focused on the water demand side of the crop for our analysis. We have estimated water requirements for early, normal and late planting dates, and reflected on high temperature duration to understand the suitability of changing planting date. This study can help with developing strategies to adapt *Boro* rice to climate change and managing water demand for crop agriculture. It will enrich our existing knowledge of optimizing

planting dates for future climate conditions and be useful for agricultural specialists and water managers of Bangladesh.

2. Methodology

2.1. Crop, study area and data collection

Three-season rice, namely *Aus*, *Aman* and *Boro* are generally cultivated in Bangladesh. *Boro* is the dry season rice, grown under a constant stagnant-water condition in the field. It is planted from December to early February, and harvested during April to June (Shelley et al., 2016). The most common cropping pattern that includes *Boro* rice is either *Boro − T.Aman − Potato* or *Boro − T.Aman − Fallow*. Bangladesh receives plenty of rainfall, which varies from 1527 to 4197 mm/year, but it is not well distributed both spatially and temporally (Shahid, 2011). Consequently, starting from 1970s, the development of groundwater irrigation has dramatically boosted *Boro* rice cropping area (Fujita, 2010). Rice plants encounter both low and high temperature stress during different growing seasons in Bangladesh (Shelley et al., 2016).

The North-West part of Bangladesh extends from 23°47′ N to 25°50′ N latitude and from 88°01′ E to 89°48′ E longitude. Four North-West districts − Bogra, Rajshahi, Pabna and Dinajpur – were selected for this study (Fig. 1). Crop data related to dry season *Boro* rice were collected from Bangladesh Agricultural Research Institute (BARI). Soil data were standardized for a medium average soil for the selected districts from FAO standard soil parameter values.

2.2. Development of climate scenarios

Five General Circulation Models (GCMs) and two emission scenarios (RCP 4.5 and 8.5) were used to construct the future climate scenarios. Maximum and minimum temperatures, rainfall, solar radiation and wind speed for 2050s and 2080s, i.e. the time series of 2035–2065 and 2065–2095 were prepared. The first GCM employed in this study was the **CNRM-CM5** model developed by CNRM-GAME (Centre National de Recherches Météorologiques—Groupe d'études de l'Atmosphère Météorologique) and Cerfacs (Centre Européen de Recherche et de Formation Avancée) to contribute to 5th phase of the Coupled Model Inter-comparison Project (CMIP5) that includes atmospheric, land surface, ocean scheme, and sea ice models (Voldoire et al., 2013). The second GCM used in this study was the **EC-Earth** model which is a seamless Earth System Model that includes forecasting and climate change studies into a single framework (Hazeleger et al., 2010). The third GCM applied in this study was **HadGEM2-ES** model which is a coupled Earth System Model used by the Met Office Hadley Centre for the CMIP5 centennial simulations. The fourth GCM used in this study was the **IPSL-CM5A-LR** model that includes 5 model components: LMDz (atmosphere), NEMO (ocean, oceanic biogeochemistry and sea-ice), ORCHIDEE (continental surfaces and vegetation), and INCA (atmospheric chemistry), coupled through OASIS. The fifth GCM employed in this study was the **MPI-ESM-LR** model which is a comprehensive Earth-System Model that consists of ocean, atmosphere and land surface component models. These models were selected for our study because of their important criteria in evaluating the impacts of climate change, such as ocean-atmosphere couple, multi-century simulation capability, well documentation in literature, and participation in the Coupled Model Inter-comparison Project (CMIP) (Barrow et al., 2004). Two different emission scenarios, RCP 4.5 and 8.5 were selected for this study since they represent realistically low and high future climate change scenarios. RCP 4.5 characterises stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq.) at stabilization after 2100 and RCP 8.5 characterises rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq.) by 2100 (Van Vuuren et al., 2011).

The future climate data for daily maximum and minimum temperatures, rainfall, solar radiation and wind speed were generated by statistical downscaling. For bias correction, the WATCH Forcing data (Weedon et al., 2011) of monthly average maximum and minimum temperatures, sunshine hours and wind speed, and monthly total rainfall were compared to the observed historical data. Since, the GCM outputs do not provide relative humidity; this was estimated following the ratio between actual and saturation vapour pressures, which are pure functions of temperature and can be calculated by a common empirical interpolation function (Holbo, 1981; WMO, 1979). For humid temperate climates, when temperature is at its daily minimum, air becomes saturated with water vapour. Hence, the general assumption to estimate relative humidity from temperature data is to consider dew point temperature as equal to the minimum temperature of the day (Eccel, 2012).

2.3. Selection of planting dates and estimation of growth duration

Two normal planting (1 and 11 December), two early planting (1 and 11 November) and two late planting (31 December and 10 January) dates were selected for analysis. Following a 35-day nursery stage, the corresponding transplanting date for normal, early and late planting is: 05-Jan & 15-Jan; 06-Dec & 16-Dec; and 04-Feb & 14-Feb. The lengths of four distinguished growth stages of *Boro* rice were estimated for each transplanting date and for different climate scenarios following the growing degree days (*GDD*) method as:

$$GDD = [(T_{max} + T_{min})/2] - T_{base} \tag{1}$$

where T_{max} is the maximum temperature (°C), T_{min} is the minimum temperature (°C), and T_{base} is the base temperature.

First, the GDD was estimated for four study districts using five climate models and two emission scenarios for each of the transplanting dates. Later, the growth stage duration was estimated from GDDs and accumulated heat values at the end of each stage as:

$$\text{Growth stage duration (days)} = \frac{\text{Accumulated heat value at the end of the stage } (^\circ C)}{\text{GDD for the corrosponding period } (^\circ C)} \tag{2}$$

The accumulated heat values (for the base temperature of 15 °C) at the end of the growth stages for *Boro* rice in the North-West zone of Bangladesh were taken from Mahmood (1997). The accumulated heat values at the end of initial, vegetative, flowering and maturing stages were 80, 528, 1052 and 1291 °C, respectively for Bogra, Rajshahi and Pabna; and 80, 515, 1032 and 1273 °C, respectively for Dinajpur. The growing degree days method can consistently predict the growth duration of crops (Miller et al., 2001).

The accumulated heat values for currently used long duration varieties (e.g. BRRI dhan29) are about 16% higher compared to short duration varieties (e.g. BRRI dhan28). Growth stage days for the possible future long-duration cultivars were estimated for Bogra. A 16% increased accumulated heat values for each stage with an imposed minimum duration for each stage was used. For the long-duration cultivar, the accumulated heat values at the end of initial, vegetative, flowering and maturing stages were 93, 613, 1221 and 1498 °C, respectively for Bogra. The imposed minimum number of days for initial, development, mid-season and late-season were 22, 45, 36 and 18 days, respectively.

2.4. Estimation of water requirements for different planting times

CropWat model was used to estimate potential crop water requirement and potential irrigation requirement for crop evapotranspiration based on climate, crop and soil data. It has been used extensively as a decision-support tool in an international context to estimate regional irrigation requirements (Clarke et al., 2001). This model was also successfully applied to evaluate impacts of climate change on water

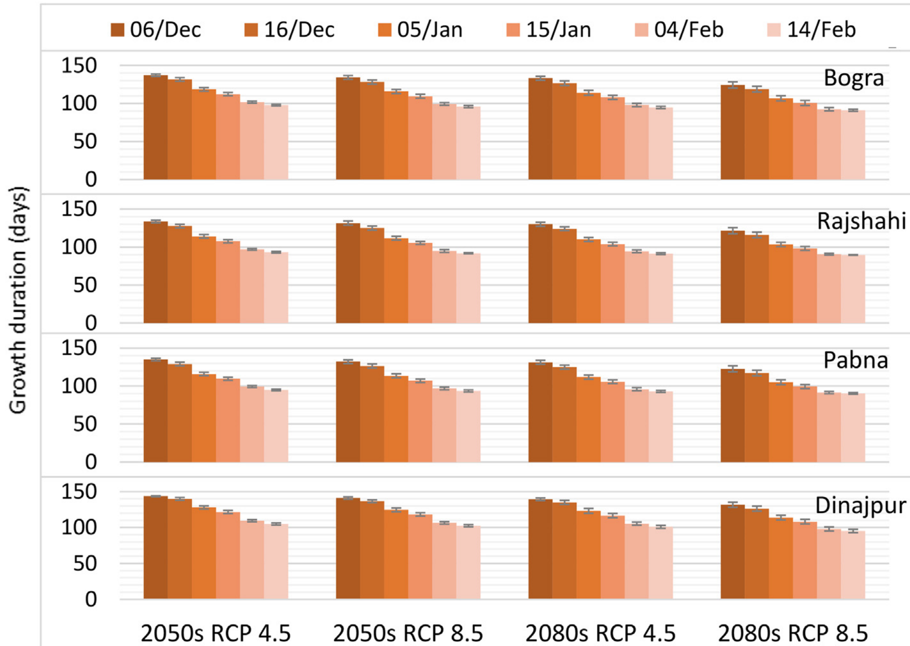

Fig. 2. Growth duration (for the average of five models) of *Boro* rice under different transplanting dates for four different climate change scenarios.

requirements in several previous researches (Chowdhury et al., 2013; Doria et al., 2006; Doria, 2010; Shrestha et al., 2013).

Water requirements of *Boro* rice were estimated using statistically downscaled bias-corrected daily climate data from GCMs outputs for four districts, five models and two RCPs for 2050s (average of 2035–65) and 2080s (average of 2065–95). *Potential crop water requirement* is calculated as total crop evapotranspiration (ΣET_C) during the crop growing period by considering changes in the length of growing season. The *Potential irrigation requirement for crop evapotranspiration* is the total amount of crop evapotranspiration in excess of effective rainfall, ER, i.e. ΣET_C-ER. The effective rainfall is the amount of rainfall that is effectively added and stored in the soil for later use by the crop and is derived as a simulation output from CropWat.

To assess the impacts of climate change on water requirements under different trans−/planting dates of *Boro* rice, the influence of management practices was excluded by modelling the rice growth in CropWat under a standardized schedule that provides irrigation water as required. The crop co-efficient values were 0.7, 0.3, 0.5, 1.05 and 0.65 under dry condition, and 1.2, 1.05, 1.1, 1.2 and 0.95 under wet condition for nursery, land preparation, initial, mid-season and late-season, respectively. The scheduling criteria to estimate the net irrigation requirement was to provide irrigation at 5 mm water depth above ground surface and refill to 100 mm standing water.

2.5. Assessment of heat stress during critical periods

Spikelet sterility may occur at different temperature thresholds (Matthews et al., 1995; Nakagawa et al., 2003) since there is genotypic variation in spikelet sterility at high temperature (Matsui et al., 2001; Prasad et al., 2006; Satake and Yoshida, 1978). Also, shorter durations at very higher temperatures may have the same effect as longer durations at relatively less higher temperatures (Satake and Matsuo, 1995). According to Laborte et al. (2012), the maximum temperature above 35 °C for 10 days can cause day time heat stress, and the minimum temperature above 25 °C for 15 days can cause night time heat stress to rice plant during the critical stages. First, we have identified the critical period to high temperature stress for early, normal and late planting for all studied districts, scenarios and climate models. For Bogra, Rajshahi and Pabna, the identified critical stress periods were the days with accumulated heat values from 659 to 1052 °C. For Dinajpur, the identified critical stress periods were the days with accumulated heat values from 644 to 1032 °C. After identification of the critical days, we identified the days with maximum temperature above 35 °C and minimum temperature above 25 °C within those critical days. The number of days with maximum temperature above 35 °C and minimum temperature above 25 °C within critical periods were counted and their percentage to total number of critical days were estimated for early, normal and late planting under all studied districts, scenarios and models to understand suitability of changing the planting date of existing (i.e. temperature intolerant) cultivars of *Boro* rice.

3. Results

3.1. Future rainfall in excess of evapotranspiration

The estimated future monthly rainfall in excess of evapotranspiration, i.e. monthly rainfall minus evapotranspiration (Appendix Fig. A1) indicates a 'wet-get-wetter' and 'dry-get-drier' situation in the North-West Bangladesh. However, the annual distribution of future rainfall in excess of evapotranspiration is almost similar to recent years in all study districts. There will be more dry conditions from November to April, which is the *Boro* growing season. The soil-water deficit or drought could be maximum during March–April. The dry months will be drier in 2080s compared to 2050s. Also, the dry months will be drier for a pronounced climate change (RCP 8.5) than a moderate climate change scenario (RCP 4.5).

The 'dry-get-drier' situation during the dry winter months could be because of less rainfall and/or increased evapotranspiration during this period. The Mann-Kendall trends of estimated reference crop evapotranspiration during the dry months of the 2035–2065 and 2065–2095 time series by Acharjee et al. (2017) indicate a possible future increase in daily evapotranspiration. The possible future monthly rainfall reveals some increasing trends (Appendix Fig. A2). The study by Shahid (2011) also indicates a significant increase (6.05 mm/year) in annual precipitation in Bogra in the long-term trends during 1958–2007. Therefore, the 'dry-get-drier' condition will be mainly because of increased evapotranspiration despite some expected increase of rainfall amount in the North-West Bangladesh.

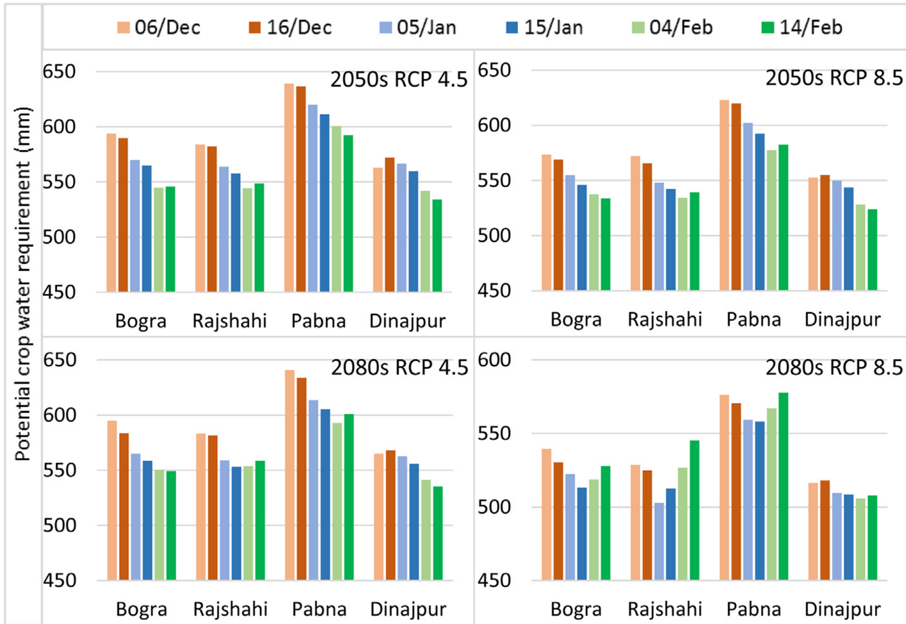

Fig. 3. Potential crop water requirement (for the average of five models) of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035−65 (2050s) and 2065−95 (2080s).

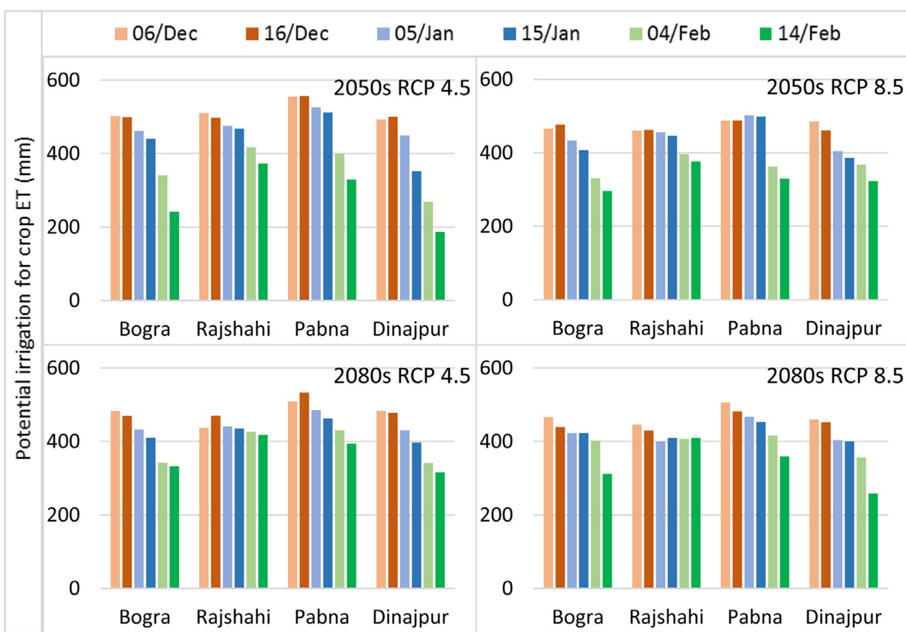

Fig. 4. Potential irrigation requirement for crop evapotranspiration (for the average of five models), $\Sigma ET_C - ER$ (mm) of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035−65 (2050s) and 2065−95 (2080s).

3.2. Future Boro growth duration under different planting dates

A shorter growth duration under late planting and a longer growth duration under early planting compared to normal time planting were observed (Fig. 2). The results are consistent for all study districts, employed models and scenarios. For the early planting, the rice plant receives a long winter period and the crop matures slowly during the low temperature period, resulting in longer growth duration. For the late panting, the rice plant receives an initial short winter period and thereafter a pre-monsoon high temperature period. Hence, the rice plant receives more number of high temperature days under the late planting compared to early planting and, therefore, matures rapidly.

3.3. Potential crop water requirements as affected by planting dates

The potential crop water requirement, ΣET_C, will increase in case of early planting and decrease in case of late planting compared to normal time planting (Fig. 3). The estimated ΣET_C are consistent for all districts, models and scenarios under consideration except in 2080s for RCP 8.5. The ΣET_C for both the early and late planting exhibit an increase compare to the normal time planting in 2080s for RCP 8.5. The difference between potential crop water requirements for early and normal planting is relatively smaller in Dinajpur compared to other districts. The potential crop water requirement is consequently higher in Pabna for all scenarios compared to other districts; this is not because of longer growth duration, but due to higher daily evapotranspiration.

The potential crop water requirement is higher in Pabna compared to other districts which is because of higher rate of daily evapotranspiration in Pabna.

The estimated potential crop water requirement exhibits a clear link with estimated growth duration of *Boro* rice under different planting dates. For early planting date, the longer growth duration resulted in increased potential crop water requirement; while for late planting, shorter growth duration resulted in reduced potential crop water requirement. However, the potential crop water requirements will increase for both early and late plantings in 2080s because of a rapid climate change. Therefore, for a rapid climate change (RCP 8.5) in the long term both early and late planting options would be ineffective in terms of crop water requirements.

3.4. Potential irrigation requirements as affected by planting dates

The potential irrigation requirement for crop evapotranspiration ($\Sigma ET_C - ER$) showed an increase for early planting and a reduction for late planting (Fig. 4). These results are consistent for all study districts, models and scenarios, including 2080s for RCP 8.5. However, the amount of reduction for the late planting is more than the amount of increase for the early planting in comparison to normal planting date.

The estimated effective rainfall during the *Boro* growth duration reveals increased rainfall availability for late planting compared to the early or normal planting (Fig. 5). The difference between rainfall availabilities for the early and normal planting dates is less than the difference between rainfall availabilities for the late and normal planting dates. Therefore, a shift from normal to early plating dates will allow a less change of rainfall availability than a shift from normal to late planting. In other words, a shift of planting date from normal to late planting can substantially increase the rainfall availability for *Boro* rice cultivation.

3.5. Temperature stress as affected by planting dates

High temperature stress reduces grain yield of rice by reducing the percentage of ripened grains as a result of spikelet sterility (Oh-e et al., 2007). The flowering and booting are the most sensitive/critical stages of rice to high temperature stress (Farrell et al., 2006; Satake and Yoshida, 1978), which may sometimes lead to complete spikelet sterility (Shah et al., 2011). For early planting, the critical period will begin during 11/Feb – 20/Mar and continue till 11/Mar – 17/Apr depending on different years, scenarios and model estimates in Bogra. For normal planting, the critical period will begin during 05/Mar – 01/Apr and continue till 28/Mar – 26/Apr. For late planting, the critical period will begin during 22/Mar – 12/Apr and continue till 12/Apr – 06/May. The detail results on estimated dates of beginning and end date of critical period of *Boro* rice in Bogra has been presented in Appendix (Fig. A.3). For a late planting critical period also begins lately. Other districts also show similar kind of results on estimated critical period dates (were estimated but has not been presented in this paper). According to Laborte et al. (2012), maximum temperature above 35 °C for 10 days during the critical period can cause a day-time heat stress and minimum temperature exceeding 25 °C for 15 days during critical period can cause a night-time heat stress.

Our results indicate that for the late planting, with critical period during late-March to early-May, there will be more chance of day-time heat stress compared to early planting having critical period during early-February to mid-April (Fig. 6). There will be also high risk of day time heat stress for normal time planting. Krishnan et al. (2011) also commented that, most agronomic interventions for dealing with high-temperature stress aim at early sowing of rice or selection of early maturing cultivars to avoid high temperatures during the grain filling stage. There will be low risk of day time heat stress in Dinajpur compared to other study districts because of less number of days with maximum temperature above 35 °C in Dinajpur.

For the late planting, there will be more chance of night-time heat stress compared to the early and normal time planting (Fig. 7). For most of the scenarios, there is no chance of night-time heat stress for the early planting. There will also be low risk of night time heat stress in Dinajpur compared to other study districts because of less number of days with minimum temperature above 25 °C in Dinajpur.

3.6. Long-duration cultivars of Boro rice as affected by planting dates

The results discussed so far is a long-duration cultivar (e.g., BR29) in the prevailing climate that will become a short-duration cultivar due to accelerated growth under increased temperature in the future; this

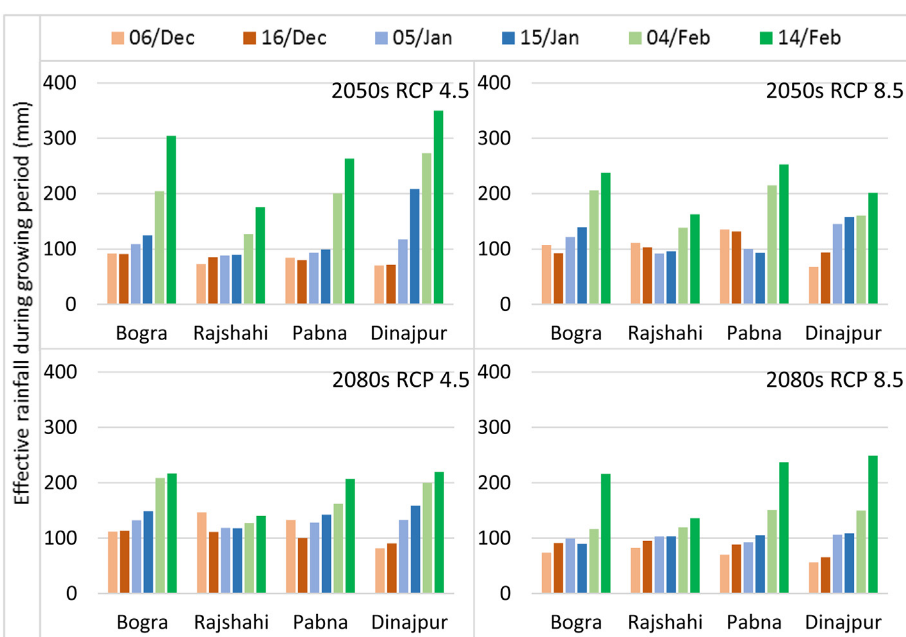

Fig. 5. Effective rainfall (for the average of five models) during Boro rice growth duration using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035−65 (2050s) and 2065−95 (2080s).

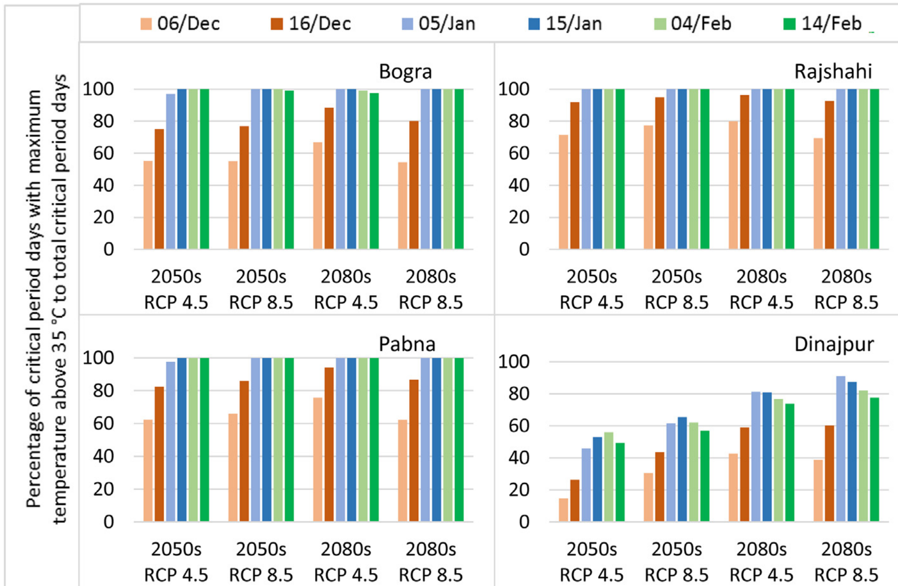

Fig. 6. Percentage of critical period days with maximum temperature above 35 °C to total critical period days (for the average of five models) for early, normal and late (trans)planting in 2050s and 2080s under RCP 4.5 and 8.5 in four study districts.

cultivar is hereafter stated as usual cultivar. A longer growth duration, usually, allows the tillers to become more mature and produce large number of panicles in winter season (Gomosta et al., 2001). Therefore, farmers may choose a possible more longer duration variety in the future that has been stated as long-duration cultivar in this study. Growth duration is an important aspect for selecting the optimum planting date. Therefore, we also presented the results for possible future long-duration cultivar of *Boro* rice (Fig. 8) and compared with the existing cultivar (Fig. 9).

Similar kind of changes in growth duration of long-duration cultivars of *Boro* rice were obtained for different planting dates like usual/short duration cultivars (Appendix, Fig. A.4). However, the percentages of increase in estimated growth duration of long duration cultivars are different for all planting dates. The percentage increase in growth duration for the late planting is higher than the percentage increase for the early planting. Therefore, the difference in growth duration between the early planting and late planting for long-duration cultivars is lower than that for usual cultivars.

Similar kind of changes in potential crop water requirements, effective rainfall and potential irrigation requirements for crop evapotranspiration of long-duration cultivars of *Boro* rice were obtained for different planting dates under investigation for the usual cultivars (Fig. 8). However, the differences between potential crop water requirements of different planting dates are smaller for the long-duration variety compared to the usual duration variety. The differences in effective rainfall and irrigation requirement between the planting dates seem larger for the long-duration variety compared to the usual duration variety. Longer growth duration, possibly, may bring more fluctuations in available rainfall because of changing trans−/planting dates.

The difference in potential crop water requirements between the long and short duration cultivars is similar for all planting dates

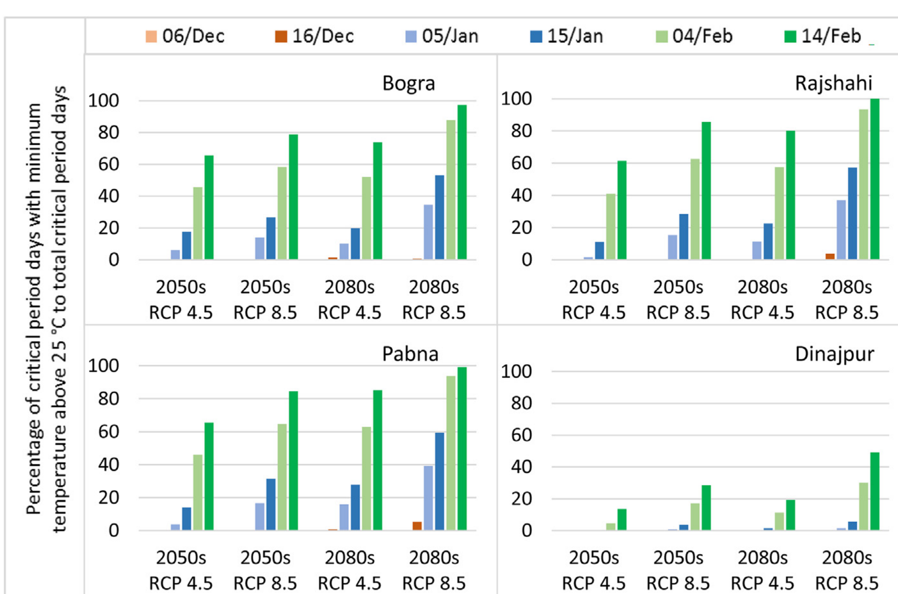

Fig. 7. Percentage of critical period days with minimum temperature above 25 °C to total critical period days (for the average of five models) for early, normal and late (trans)planting in 2050s and 2080s under RCP 4.5 and 8.5 in four study districts.

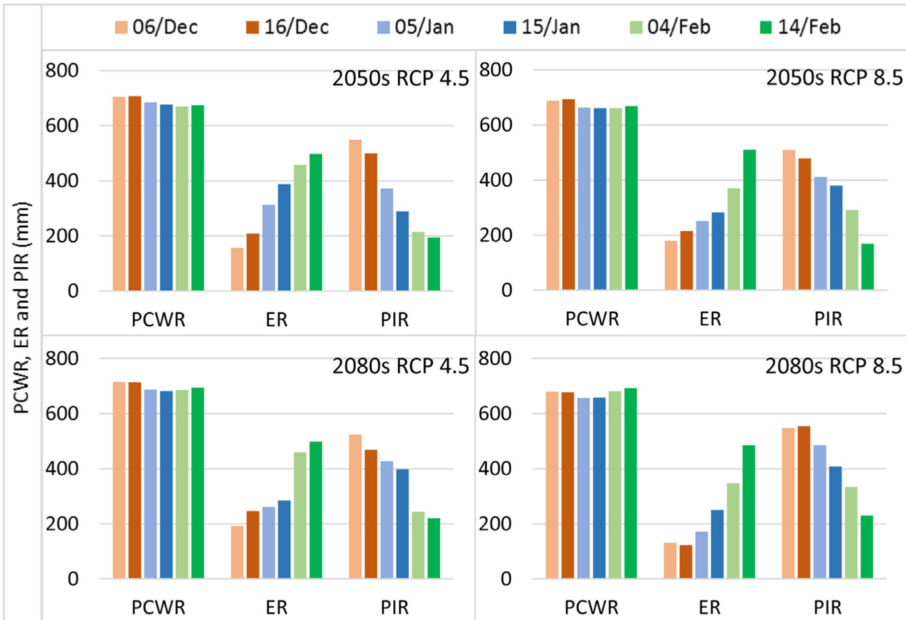

Fig. 8. Potential crop water requirement (PCWR), effective rainfall during crop growing period (ER) and potential irrigation requirement for crop evapotranspiration (PIR) for long-duration cultivar of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s) in Bogra district.

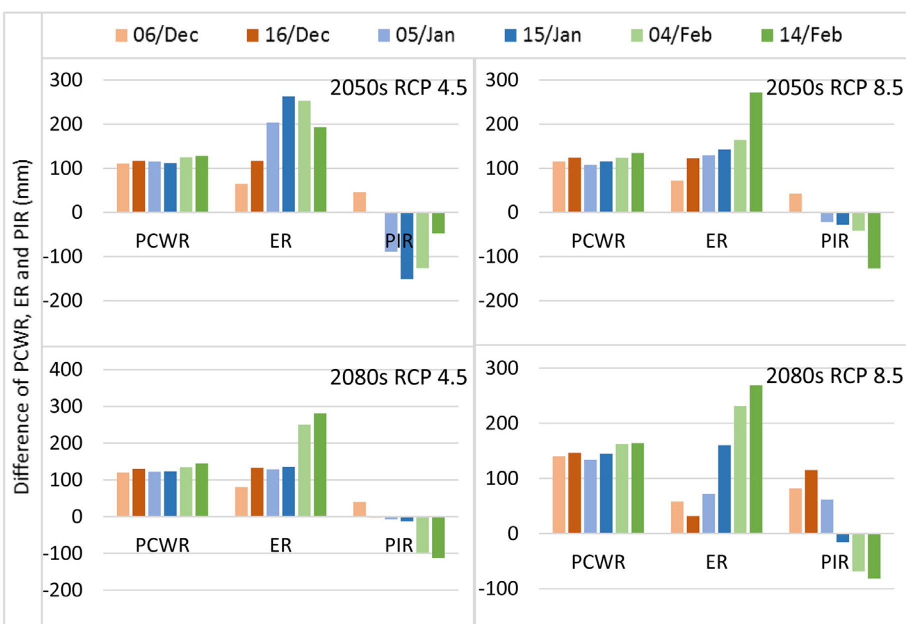

Fig. 9. Difference in potential crop water requirement (PCWR), effective rainfall during crop growing period (ER) and potential irrigation requirement for crop evapotranspiration (PIR) of long-duration cultivar compared to usual duration cultivar of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s) in Bogra district.

(Fig. 9). However, the difference in effective rainfalls and potential irrigation requirements between the long and short duration cultivars is different for all planting dates. In 2080s for RCP 4.5 and in 2050s for RCP 8.5, the variation in potential irrigation requirement differences is much more between normal and late planting compared to normal and early planting. This indicates that irrigation requirements may change drastically from long to short duration cultivars between normal and late planting dates for moderate climate change in 2080s or rapid climate change in 2050s. The decrease in potential irrigation requirements for long-duration cultivar compared to usual duration cultivar is because of more rainfall availability during the later stages of the growing season.

4. Discussion

Several factors may affect the choice of the best or optimum planting date. One of the main concerns for this choice is the amount of water needed for cultivation of the crop, especially in water-limited areas or drought-prone regions. Since, lack of water during dry season is the major concern in the North-West Bangladesh, we have analysed water requirements for different planting dates of *Boro* rice.

4.1. Future Boro growth duration: estimates and possibilities

The study by Kabir et al. (2016) indicates that, the growth duration of two transplanted *Boro* varieties (45-days old seedling) in the recent climate (2001) varied about 5 and 10 days for one month shifting of transplanting date from 15 December to 13 January. In our study, for one month shifting of transplanting date from 16 December to 15 January of 35-days old seedling, the growth duration reduced 19 days in the future. The increased variation in growth duration for one month shifting of transplanting in our study is because of an accelerated accumulation of GDD due to more rapid future climate change compared to recent climate change.

There are two main aspects of future growth duration of *Boro* rice: firstly, the changes in growth duration of current cultivars because of increased temperature in the future, and, secondly, the growth duration of possible new cultivars. Our estimates clearly indicate a considerable influence of temperature difference, due to shifts in planting date, on the growth duration of existing *Boro* cultivar under future climate scenarios (Fig. 2). Rice matures rapidly during the warmer late period compared to the cooler earlier period. However, the exact reduced number of days for a late planting or increased number of days for an early planting may be different for different *Boro* cultivars. As the future shortening of growth duration can substantially reduce the rice yield, farmers may need to change to a long-duration cultivar in the future to maintain their yields. However, the influence of shifting planting date is similar for both short and long-duration cultivars.

4.2. Potential crop water and irrigation requirements as influenced by planting date

A delay in planting time of *Boro* rice reduces potential crop water and irrigation requirements by enhancing the crop maturity compared to early planting. Compared to the early planting, the potential crop water requirements (averaged over all districts and models) reduced by 6.5 and 5.9% in 2050s for RCP 4.5 and 8.5, respectively, and by 5.7 and 0.6% in 2080s for RCP 4.5 and 8.5, respectively in case of late planting. The potential irrigation requirement for crop evapotranspiration (averaged over all districts and models) for late planting was reduced by 31 and 21% in 2050s for RCP 4.5 and 8.5, respectively, and by 14% in 2080s for both RCP 4.5 and 8.5 compared to normal planting dates. The potential irrigation requirement for crop evapotranspiration for late planting was reduced by 38 and 27% in 2050s for RCP 4.5 and 8.5, respectively, and by 22 and 21% in 2080s for both RCP 4.5 and 8.5 compared to early planting. The reduction in irrigation requirements for late planting is caused by high rainfall availability during the later parts of the growing season. Late planting in winter, generally, ensures a higher rainfall during the vegetative growth and brings some beneficial effects by reducing the possibility of water stress (Karim et al., 2012). The reduced crop growth duration and better rainfall accessibility for the late planting dates ensure a much lower irrigation requirement for *Boro* rice. Therefore, the late planting is a good choice for the future from a water demand perspective.

A later planting date can substantially reduce the amount of irrigation required for *Boro* cultivation, but may reduce yield due to heavy rainfall events before harvesting. Perez and Hosen (1987) reported that rain can cause delay in harvest and increase proportion of broken grains during milling. The number of heavy rainfall events will increase in the future against a decrease in total rainy days in a year (Wassmann and Dobermann, 2007); this can potentially reduce water availability for crop growth because during heavy rainfall events runoff is relatively high and there is only limited water infiltration into the soil (Challinor et al., 2004). Another major concern for late planting is the reduced growth duration. Higher temperatures, by accelerating plant growth rate, reduce growth duration leading to shorter grain filling period, varying from 25 days in tropics to 35 days in temperate zones (Swaminithan, 1984). However, selection of a suitable crop variety can mitigate the impact of higher temperatures (Challinor et al., 2005). Therefore, a suitable crop variety that can withstand higher temperatures and heavy rainfall events is required for late planting strategies.

4.3. Planting date related temperature stress on Boro rice

The panicle initiation stage is sensitive to low-temperature damage, whereas the flowering stage is more sensitive to high-temperatures; both cases can cause spikelet sterility (Shelley et al., 2016). At present, early planted *Boro* rice in Bangladesh often faces low-temperature stress at both vegetative and reproductive stages (Nahar et al., 2009). In contrast, the late *Boro* rice often encounters high temperature stress at the reproductive stage (Shelley et al., 2016). Our study indicate a high chance of temperature stress for normal and late planting. The yield of *Boro* rice may decline with late sowing due to greater exposure to high temperature during anthesis (Ahmed et al., 2016). A study in Sri Lanka by Dharmarathna et al. (2014) indicates that dry season rice yield would increase when the planting date is advanced by one month. Both daily maximum and minimum temperatures will increase in the future due to global warming, which will reduce the chance of low-temperature damage during panicle initiation but increase the risk of high-temperature damage during booting and flowering. Both day- and night-time high-temperatures are likely to become more crucial in the future. Our results indicate that, day time heat stress can be more crucial than the night time heat stress for *Boro* rice in the North-West Bangladesh. The night time heat stress can be avoided by selecting an early planting date. However, *Boro* rice may be affected by day time heat stress even in case of early planting. More studies on *Boro* rice cultivars are required to minimize the heat stress induced spikelet sterility. Studies on heat escape mechanism by early-morning flowering (Bheemanahalli et al., 2017; Hirabayashi et al., 2014; Ishimaru et al., 2010), heat avoidance through transpiration cooling (Julia and Dingkuhn, 2013), and heat tolerance to increase resilience by altering cellular metabolites (Jagadish et al., 2009) need more attention. A high-temperature tolerant rice variety is, therefore, highly recommended for this region and, thereafter, a date between normal and late planting may be chosen based on temperature-tolerance capacity of the selected cultivar. Otherwise, an early planting would be more suitable to avoid the risk of high temperature stress and, in such a case, other options of water demand management need to be explored instead of the delayed planting option for the reduction of water use.

4.4. Planting date change: an adaptation strategy

For wet season crops like *Aman* rice, farmers can adjust planting date following the availability of rainfall. The erratic intensity and distribution of pre-monsoon rainfall contributes to considerable variations in sowing dates between different areas, sometimes within short distances (Brammer, 1987). However, for dry season crops like *Boro* rice, it is more difficult to choose a suitable trans−/planting date, because the rainfall availability varies during the time period when the rice plant requires it most.

Changing planting date may provide some adaptation options, but that will be limited in the Indo-Gangetic plain by low winter temperatures (Wassmann and Dobermann, 2007). Our results indicate, the option of changing planting date, as an adaptation strategy, will be limited by high temperature stress, especially in the case of late planting choices. In the Indo-Gangetic plain, delayed planting is a well-recognized cause of yield reduction in rice and wheat (Wassmann and Dobermann, 2007). Therefore, identification of the best or optimum planting date may be a great challenge for the future, especially in case of non-availability of temperature-tolerant varieties.

The risk of yield reduction of *Boro* rice due to both heat stress and heavy rainfall/storm during harvesting period is high for the late planting. Since, the heat-stress induced risk may not vary much throughout the study region, it can be eliminated by choosing a temperature-tolerant variety. But, the heavy shower/storm-related risk can considerably vary depending on local geographic conditions, drainage capacity, etc. in the region. Estimation of return period and better forecast of extreme rainfall events/storms can help to reduce this risk.

Since irrigation demand is much less for late planting, farmers under water-limited situation can be recommended to choose a late-planting date taking into account of the impacts of high temperature stress. Karim et al. (2012) reported significant reduction in rice yield due to lack of available water for early planting, especially before 28th January. The main limitation of late planting is the increased chance of temperature stress during the critical stage of *Boro* rice. Climate change may expose rice yield more vulnerable to transplanting date, predicting

significant yield reduction as transplanting date is delayed, especially after 15 January (Basak et al., 2009). Another concern for late planting is the increased possibility of heavy rainfall during rice harvesting that cause crop failure. Late planting may also prevent the next crop from being obtained the suitable condition later in the season (Matthews et al., 1997). However, the late planting of temperature-tolerant cultivars would be the best choice for water-limited regions. For regions with high water availability, the early planting of a long-duration high-yielding cultivar would be the optimal choice in the future. Any long-duration variety is not recommended for the low-lying *Haor* areas where flash floods may cause damage to *Boro* rice before harvesting.

Many investigators at several agricultural research institutes are working to improve rice cultivars by incorporating tolerance to drought, flood and salinity. Most rice varieties, so far developed in Bangladesh, cannot withstand high-temperature stresses (Shelley et al., 2016). Development of heat-tolerant rice cultivars is, therefore, highly recommended. This will not only increase crop yield but may also reduce irrigation requirement by adjusting planting date.

5. Conclusions

A delay in trans-/planting date enhances maturity of *Boro* rice and, consequently, reduces potential crop water requirement compared to early planting. Further reduction in irrigation requirement under late planting occurs because of increased rainfall availability during the later periods of crop growth. Hence, the late planting is a good choice for the future from a water demand perspective. However, there will be more chances of both day- and night-time heat stress for late compared to early planting strategies of *Boro* rice. Shift of trans−/planting dates may bring more fluctuations in available rainfall and irrigation requirements for long duration cultivars than short duration cultivars. Although, shifting the planting date of the crop has the potential to substantially reduce irrigation requirement, the option is, however, highly limited by the possible high temperature stress. Therefore, development of temperature-tolerant rice variety is a pre-requisite to reduce irrigation requirement by choosing late trans−/planting date.

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Appendix A

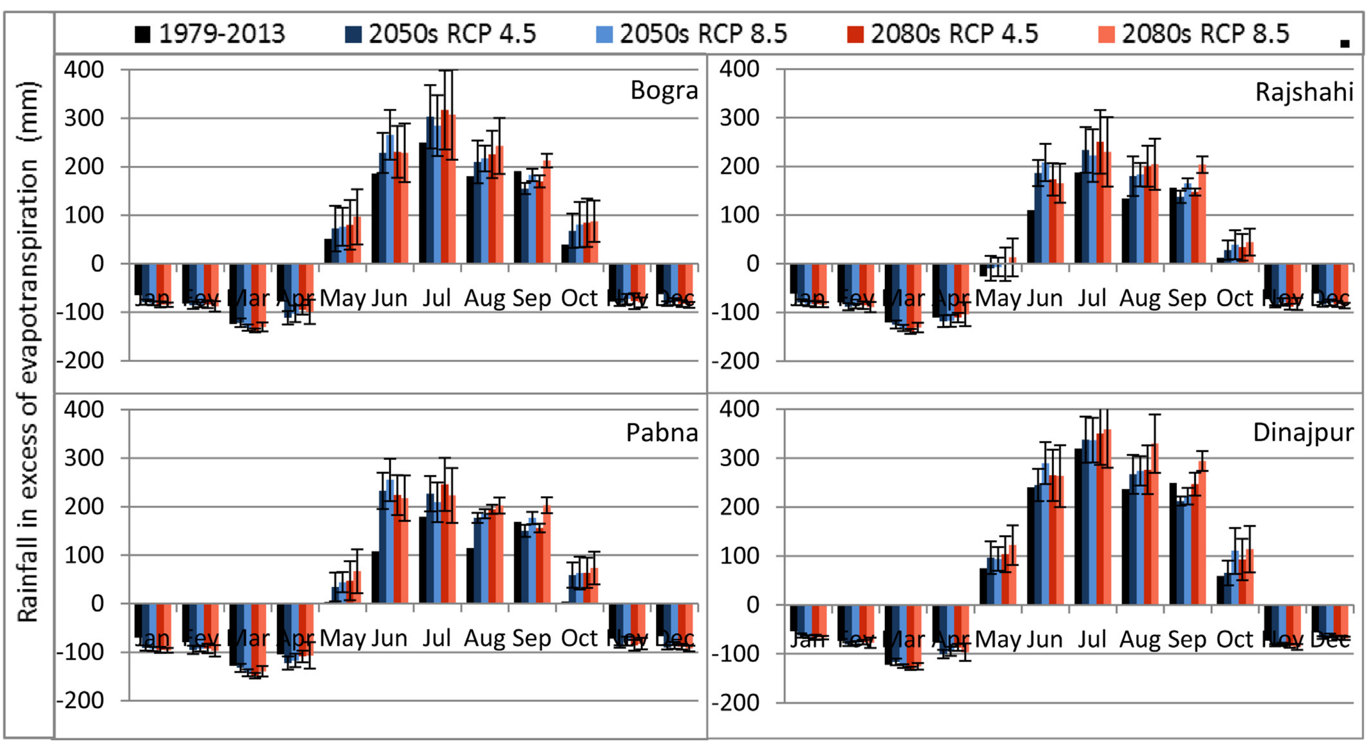

Fig. A.1. Future changes in monthly rainfall in excess of evapotranspiration.

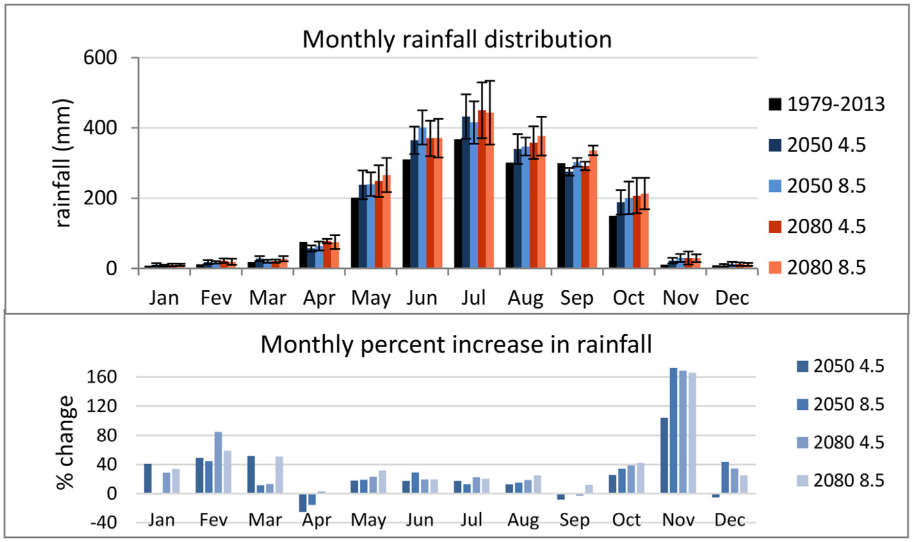

Fig. A.2. Future monthly rainfall distribution and percent change (average of five models) in Bogra district; the error bars indicate variations by different model estimates.

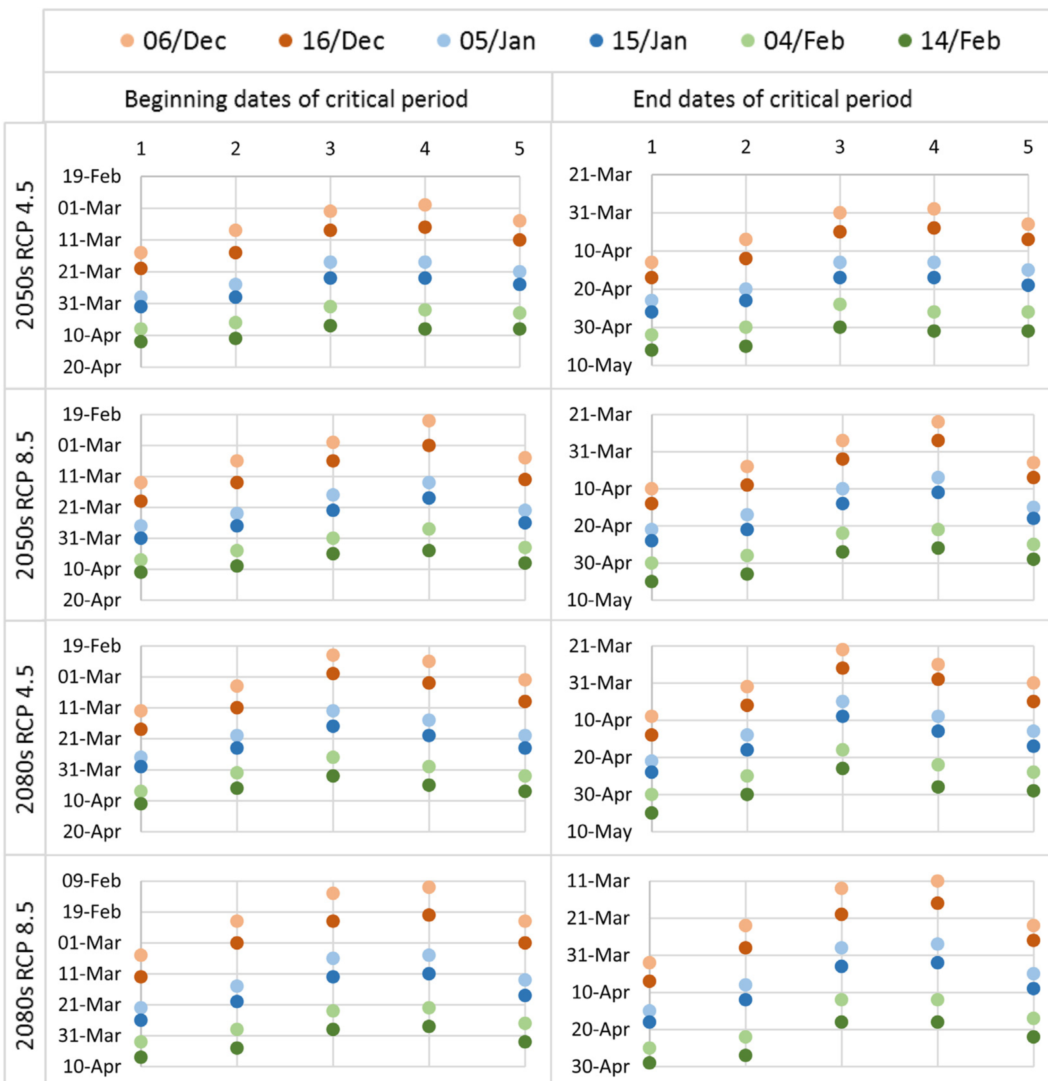

Fig. A.3. Estimated beginning and end date of critical period of *Boro* rice in Bogra under six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035−65 (2050s) and 2065−95 (2080s) for five models (1 = CNRM-CM5, 2 = EC-Earth, 3 = HadGEM2-ES, 4 = IPSL-CM5A-LR, and 5 = MPI-ESM-LR).

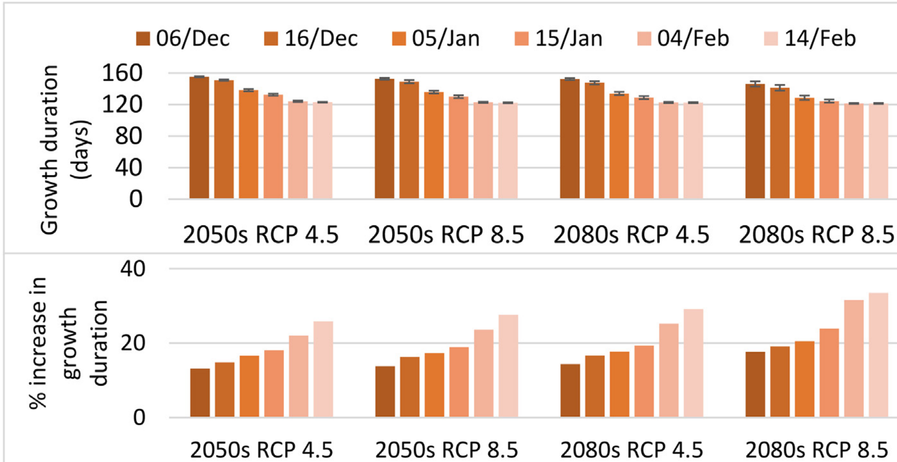

Fig. A.4. Growth-stage-days and percent increase in growth-stage-days (average of five models) for long-duration cultivars (top) compared to that for usual cultivars (bottom) for six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035−65 (2050s) and 2065−95 (2080s) in Bogra.

References

Acharjee, T.K., Halsema, G., Ludwig, F., Hellegers, P., 2017. Declining trends of water requirements of dry season Boro rice in the North-West Bangladesh. Agric. Water Manag. 180, 148–159.

Acharjee, T.K., Ludwig, F., van Halsema, G., Hellegers, P., Supit, I., 2017. Future changes in water requirements of Boro rice in the face of climate change in North-West Bangladesh. Agric. Water Manag. 194, 172–183.

Ahmed, S., Humphreys, E., Chauhan, B.S., 2016. Optimum sowing date and cultivar duration of dry-seeded boro on the high Ganges river floodplain of Bangladesh. Field Crop Res. 190, 91–102.

Barrow, E., Maxwell, B., Gachon, P., 2004. Climate Variability and Change in Canada: Past, Present and Future. ACSD science assessment series.

Basak, J.K., Ali, M.A., Islam, M.N., Alam, M.J.B., 2009. Assessment of the effect of climate change on boro rice production in Bangladesh using CERES-Rice model. In: Proceedings of the International Conference on Climate Change Impacts and Adaptation Strategies for Bangladesh, pp. 103–113.

Basak, J.K., Ali, M.A., Islam, M.N., Rashid, M.A., 2010. Assessment of the effect of climate change on boro rice production in Bangladesh using DSSAT model. J. Civ. Eng. 38, 95–108 IEB).

Bates, B., Kundzewicz, Z., Wu, S., 2008. Climate Change and Water. Intergovernmental Panel on Climate Change Secretariat.

Bheemanahalli, R., Sathishraj, R., Manoharan, M., Sumanth, H., Muthurajan, R., Ishimaru, T., Krishna, J.S., 2017. Is early morning flowering an effective trait to minimize heat stress damage during flowering in rice? Field Crop Res. 203, 238–242.

Biemans, H., Speelman, L., Ludwig, F., Moors, E., Wiltshire, A., Kumar, P., Gerten, D., Kabat, P., 2013. Future water resources for food production in five South Asian river basins and potential for adaptation—A modeling study. Sci. Total Environ. 468, S117–S131.

Brammer, H., 1987. Drought in Bangladesh: lessons for planners and administrators. Disasters 11, 21–29.

Challinor, A., Wheeler, T., Craufurd, P., Slingo, J., 2005. Simulation of the impact of high temperature stress on annual crop yields. Agric. For. Meteorol. 135, 180–189.

Challinor, A., Wheeler, T., Craufurd, P., Slingo, J., Grimes, D., 2004. Design and optimisation of a large-area process-based model for annual crops. Agric. For. Meteorol. 124, 99–120.

Chowdhury, S., Al-Zahrani, M., Abbas, A., 2013. Implications of Climate Change on Crop Water Requirements in Arid Region: An Example of Al-Jouf. Journal of King Saud University – Engineering Sciences, Saudi Arabia.

Chun, J.A., Li, S., Wang, Q., Lee, W.-S., Lee, E.-J., Horstmann, N., Park, H., Veasna, T., Vanndy, L., Pros, K., 2016. Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. Agric. Syst. 143, 14–21.

Clarke, D., Smith, M., El-Askari, K., 2001. CropWat for Windows: User Guide. (IHE.).

Dharmarathna, W., Herath, S., Weerakoon, S., 2014. Changing the planting date as a climate change adaptation strategy for rice production in Kurunegala district, Sri Lanka. Sustain. Sci. 9, 103–111.

Doria, R.O., 2010. Impact of Climate Change on Crop Water Requirements in Eastern Canada. Department of Bioresource Engineering. McGill University.

Doria, R., Madramootoo, C., Mehdi, B., 2006. Estimation of Future Crop Water Requirements for 2020 and 2050, Using CROPWAT, EIC Climate Change Technology. IEEE. pp. 1–6.

Eccel, E., 2012. Estimating air humidity from temperature and precipitation measures for modelling applications. Meteorol. Appl. 19, 118–128.

Farrell, T., Fox, K., Williams, R., Fukai, S., 2006. Genotypic variation for cold tolerance during reproductive development in rice: screening with cold air and cold water. Field Crop Res. 98, 178–194.

Fujita, K., 2010. Re-Thinking Economic Development. The Green Revolution, Agrarian Structure and Transformation in Bangladesh. Kyoto University Press, Japan.

Gomosta, A., Quayyum, H., Mahbub, A., 2001. Tillering Duration and Yielding Ability of Rice Varieties in the Winter Rice Season of Bangladesh. International Rice Research Conference, Los Baños, Laguna (Philippines) 31 Mar-3 Apr 2000. IRRI.

Hazeleger, W., Severijns, C., Semmler, T., Stefanescu, S., Yang, S., Wang, X., Wyser, K., Dutra, E., Baldasano, J.M., Bintanja, R., 2010. EC-Earth. Bull. Am. Meteorol. Soc. 91, 1357.

Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, G.E., Lasco, R.D., Lindgren, E., Surjan, A., 2014. Asia. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1327–1370.

Hirabayashi, H., Sasaki, K., Kambe, T., Gannaban, R.B., Miras, M.A., Mendioro, M.S., Simon, E.V., Lumanglas, P.D., Fujita, D., Takemoto-Kuno, Y., 2014. qEMF3, a novel QTL for the early-morning flowering trait from wild rice, Oryza officinalis, to mitigate heat stress damage at flowering in rice, O. sativa. J. Exp. Bot. 66, 1227–1236.

Holbo, H., 1981. A dew-point hygrometer for field use. Agric. Meteorol. 24, 117–130.

IPCC, 2013. Summary for Policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ishimaru, T., Hirabayashi, H., Ida, M., Takai, T., San-Oh, Y.A., Yoshinaga, S., Ando, I., Ogawa, T., Kondo, M., 2010. A genetic resource for early-morning flowering trait of wild rice Oryza officinalis to mitigate high temperature-induced spikelet sterility at anthesis. Ann. Bot. 106, 515–520.

Jagadish, S., Muthurajan, R., Oane, R., Wheeler, T.R., Heuer, S., Bennett, J., Craufurd, P.Q., 2009. Physiological and proteomic approaches to address heat tolerance during anthesis in rice (Oryza sativa L.). J. Exp. Bot. 61, 143–156.

Julia, C., Dingkuhn, M., 2013. Predicting temperature induced sterility of rice spikelets requires simulation of crop-generated microclimate. Eur. J. Agron. 49, 50–60.

Kabir, M., Howlader, M., Biswas, J., Mahbub, M., Elahi, M.N.E., 2016. Probability of low temperature stress at different growth stages of Boro rice. Bangladesh Rice J 19, 19–27.

Karim, M.R., Ishikawa, M., Ikeda, M., Islam, M.T., 2012. Climate change model predicts 33% rice yield decrease in 2100 in Bangladesh. Agron. Sustain. Dev. 32, 821–830.

Krishnan, P., Ramakrishnan, B., Reddy, K.R., Reddy, V., 2011. High-temperature effects on rice growth, yield, and grain quality. In: Advances in Agronomy. Elsevier, pp. 87–206.

Laborte, A., Nelson, A., Jagadish, K., Aunario, J., Sparks, A., Ye, C., Redoña, E., 2012. Rice feels the heat. In: Rice Today, July–September, 30–31.

Mahmood, R., 1997. Impacts of air temperature variations on the boro rice phenology in Bangladesh: implications for irrigation requirements. Agric. For. Meteorol. 84, 233–247.

Mainuddin, M., Kirby, M., Hoanh, C.T., 2011. Adaptation to climate change for food security in the lower Mekong Basin. Food Security 3, 433–450.

Matsui, T., Omasa, K., Horie, T., 2001. The difference in sterility due to high temperatures during the flowering period among japonica-rice varieties. Plant Production Science 4, 90–93.

Matthews, R.B., Kropff, M.J., Bachelet, D., van Laar, H.H., 1995. Modeling the impact of climate change on rice production in Asia. Int. Rice Res. Inst.Modeling the impact of climate change on rice production in Asia. Int. Rice Res. Inst.

Matthews, R., Kropff, M., Horie, T., Bachelet, D., 1997. Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. Agric. Syst. 54, 399–425.
Miller, P., Lanier, W., Brandt, S., 2001. Using growing degree days to predict plant stages. In: Ag/Extension Communications Coordinator, Communications Services. Montana State University-Bozeman, Bozeman, MO.
Mojid, M., Rannu, R., Karim, N., 2015. Climate change impacts on reference crop evapotranspiration in North-West hydrological region of Bangladesh. Int. J. Climatol. 35, 4041–4046.
Nahar, K., Biswas, J., Shamsuzzaman, A., Hasanuzzaman, M., Barman, H., 2009. Screening of indica rice (Oryza sativa L.) genotypes against low temperature stress. Bot. Res. Int 2, 295–303.
Nakagawa, H., Horie, T., Matsui, T., 2003. Effects of climate change on rice production and adaptive technologies. In: International Rice Research Conference. International Rice Research Institute, Beijing, China 16–19 September 2002.
Oh-E, I., Saitoh, K., Kuroda, T., 2007. Effects of high temperature on growth, yield and dry-matter production of rice grown in the paddy field. Plant Production Sci 10, 412–422.
Parry, M., Canziani, O., Palutikof, J., van der Linden, P.J., Hanson, C.E., 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge.
Perez, F., Hosen, A., 1987. Effect of Simulated Rain on Head Rice Yields of Varieties Under Delayed Harvest. (International Rice Research Newsletter (Philippines)).
Prasad, P., Boote, K., Allen Jr., L., Sheehy, J., Thomas, J., 2006. Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. Field Crop Res. 95, 398–411.
Satake, T., Matsuo, T., 1995. High temperature injury, Science of the rice plant. Food Agricultural Policy Res Centre 2, 805–812.
Satake, T., Yoshida, S., 1978. High temperature-induced sterility in indica rices at flowering. Japanese J. Crop Science 47, 6–17.
Shah, F., Huang, J., Cui, K., Nie, L., Shah, T., Chen, C., Wang, K., 2011. Impact of high-temperature stress on rice plant and its traits related to tolerance. J. Agric. Sci. 149, 545–556.
Shahid, S., 2011. Trends in extreme rainfall events of Bangladesh. Theor. Appl. Climatol. 104, 489–499.
Shelley, I.J., Takahashi-Nosaka, M., Kano-Nakata, M., Haque, M.S., Inukai, Y., 2016. Rice Cultivation in Bangladesh: Present Scenario, Problems, and Prospects.
Shrestha, S., Gyawali, B., Bhattarai, U., 2013. Impacts of Climate Change on Irrigation Water Requirements for Rice–Wheat Cultivation in Bagmati River Basin. Nepal.
Swaminithan, M.S., 1984. Rice. Sci. Am 250, 81–93.
Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., 2011. The representative concentration pathways: an overview. Clim. Chang. 109, 5–31.
Voldoire, A., Sanchez-Gomez, E.Y., Mélia, D.S., Decharme, B., Cassou, C., Sénési, S., Valcke, S., Beau, I., Alias, A., Chevallier, M., 2013. The CNRM-CM5. 1 global climate model: description and basic evaluation. Clim. Dyn. 40, 2091–2121.
Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F.T., Stacke, T., 2013. Multimodel projections and uncertainties of irrigation water demand under climate change. Geophys. Res. Lett. 40, 4626–4632.
Wassmann, R., Dobermann, A., 2007. Climate Change Adaptation through Rice Production in Regions with High Poverty Levels.
Weedon, G., Gomes, S., Viterbo, P., Shuttleworth, W.J., Blyth, E., Österle, H., Adam, J., Bellouin, N., Boucher, O., Best, M., 2011. Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century. J. Hydrometeorol. 12, 823–848.
WMO, 1979. Technical Regulations. I WMO, Geneva, Switzerland pp. I-Ap-C-3.
Yoshida, S., 1981. Fundamentals of rice crop science Int. Rice Res. Inst.Fundamentals of rice crop science Int. Rice Res. Inst.